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Neutrinos and Cosmology

Strenghts and weaknesses of cosmological bounds on effective number and masses of neutrinos

European Neutrino "Town" Meeting, CERN, 22–24/10/2018

Three Neutrino Oscillations

Analogous to CKM mixing for quarks:

[Pontecorvo, 1968]
[Maki, Nakagawa, Sakata, 1962]

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau)$$

ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

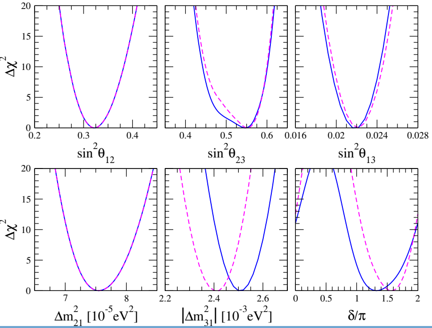
Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

$\Delta m^2_{ji} = m^2_j - m^2_i$, θ_{ij} mixing angles
NO: Normal Ordering, $m_1 < m_2 < m_3$
IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\Delta m^2_{21} = (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

$$\sin^2(\theta_{12}) = 0.320^{+0.020}_{-0.016}$$
$$\sin^2(\theta_{13}) = 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO})$$
$$= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO})$$
$$\sin^2(\theta_{23}) = 0.547^{+0.020}_{-0.030}\ (\mathrm{NO})$$
$$= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO})$$

First hints for $\delta_{\rm CP} \simeq 3/2\pi$



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see also: http://globalfit.astroparticles.es

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$= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}$ [illegible]

$\sin^2(\theta_{12})$ [illegible]

$\sin^2$[illegible] $= $[illegible]$10^{+0.008}_{-0.007}$ (NO)

$= 0.0222^{+0.007}_{-0.008}$ (IO)

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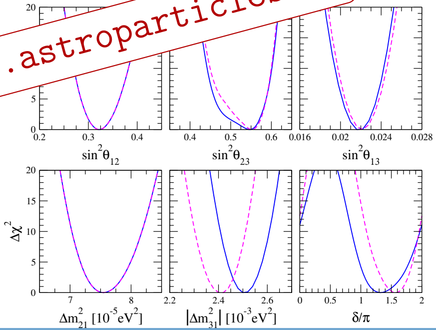
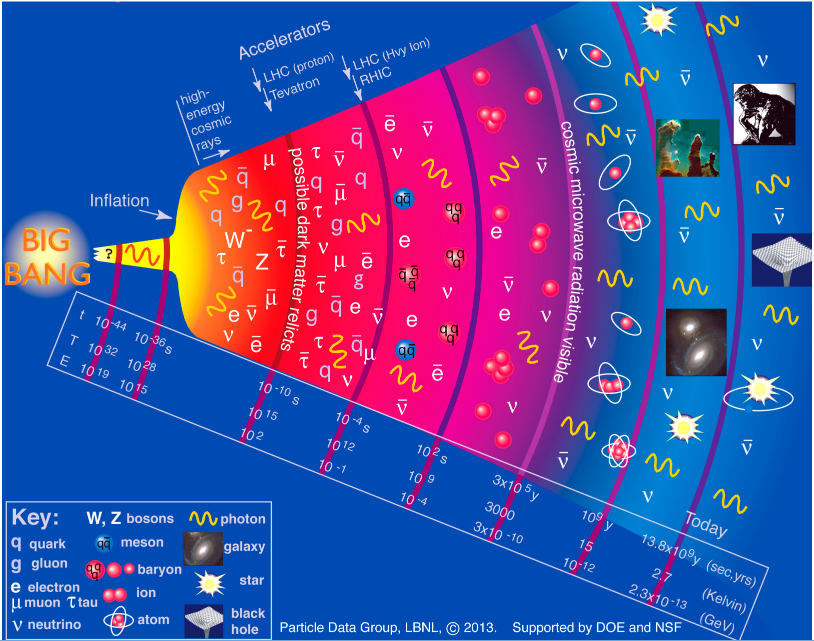


History of the universe



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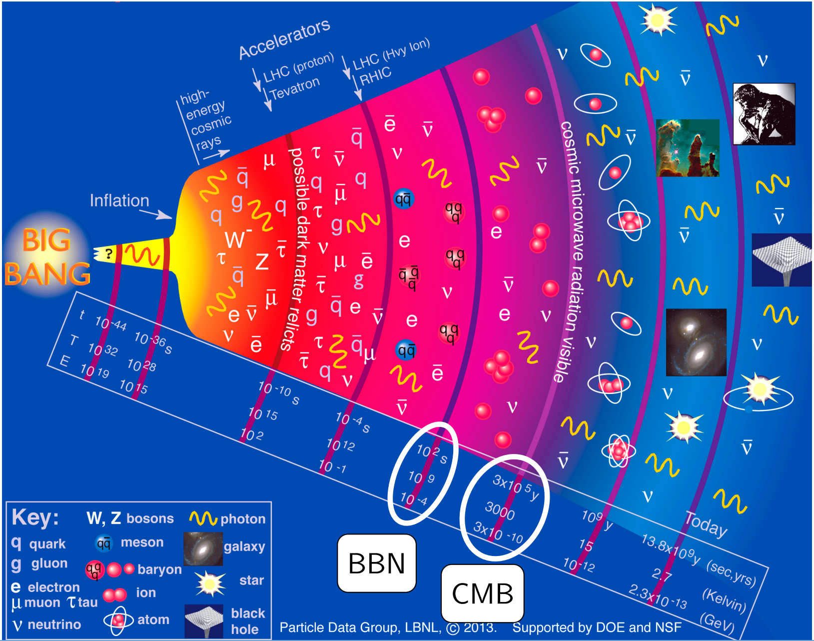

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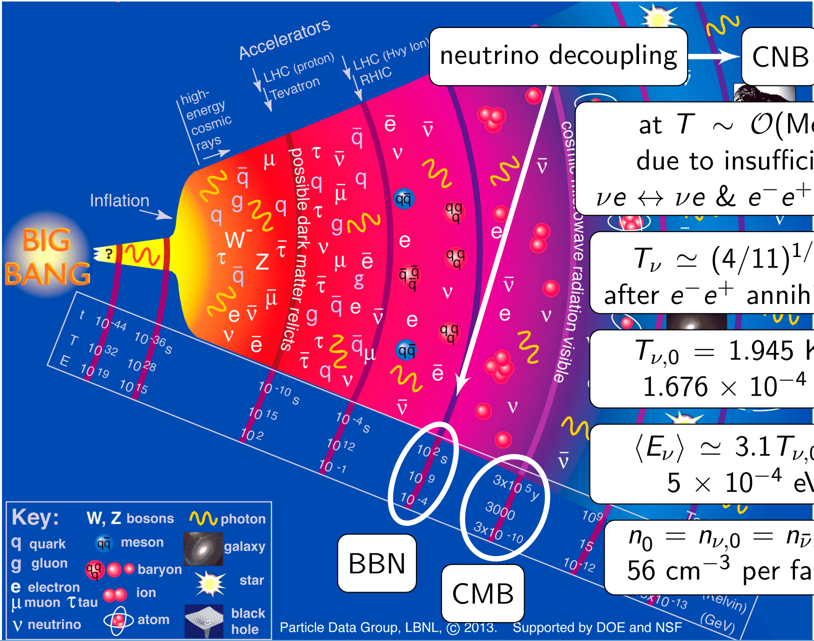

neutrino decoupling → CNB

BBN

CMB

at $T \sim \mathcal{O}(\mathrm{MeV})$ due to insufficient $\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

$T_\nu \simeq (4/11)^{1/3} T_\gamma$ after $e^- e^+$ annihilation

$T_{\nu,0} = 1.945\ \mathrm{K} \simeq 1.676 \times 10^{-4}\ \mathrm{eV}$

$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq 5 \times 10^{-4}\ \mathrm{eV}$

$n_0 = n_{\nu,0} = n_{\bar{\nu},0} \simeq 56\ \mathrm{cm}^{-3}$ per family

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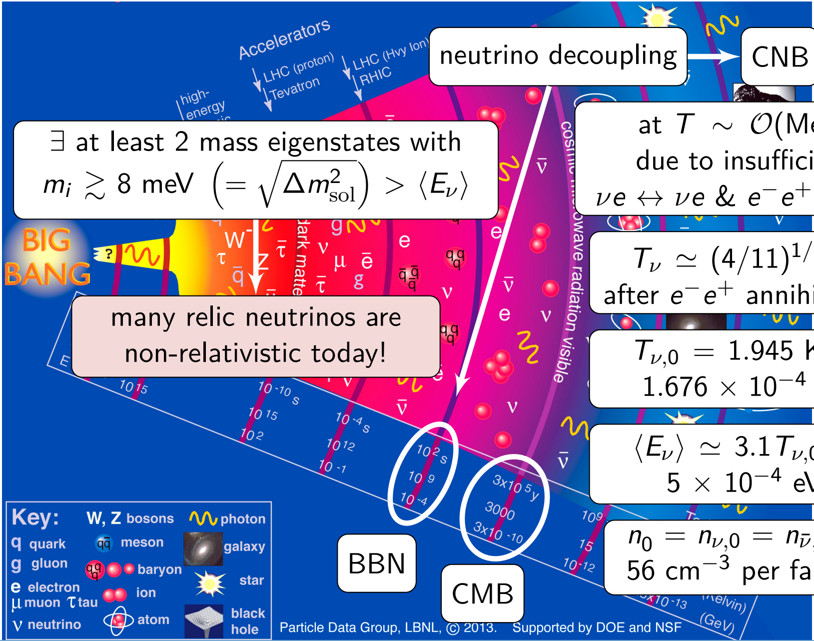

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$\exists$ at least 2 mass eigenstates with
$m_i \gtrsim 8\ \mathrm{meV}\ \left(= \sqrt{\Delta m^2_{\rm sol}}\right) > \langle E_\nu \rangle$

many relic neutrinos are non-relativistic today!

BBN

CMB

Relic neutrinos in cosmology: $N_{\rm eff}$

Radiation energy density ρ_r in the early Universe:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma = [1 + 0.2271 N_{\rm eff}]\,\rho_\gamma$$

ρ_γ photon energy density, 7/8 is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\rm eff} \rightarrow$ all the radiation contribution not given by photons
- $N_{\rm eff} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos:
  $N_{\rm eff} = 3.046$ [Mangano et al., 2005] (damping factors approximations) $\sim$
  $N_{\rm eff} = 3.045$ [de Salas et al., 2016] (full collision terms)
  due to not instantaneous decoupling for the neutrinos
- $+$ Non Standard Interactions: $3.040 < N_{\rm eff} < 3.059$ [de Salas et al., 2016]

Observations: $N_{\rm eff} \simeq 3.0 \pm 0.2$ [Planck 2018]
Indirect probe of cosmic neutrino background!

$\gg 10\sigma$!

Additional Radiation in the Early Universe

$\rho_r = [1 + 0.2271 N_{\text{eff}}]\, \rho_\gamma$

$H^2 = 8\pi G \rho_T / 3$

N_{eff} controls the expansion rate H in the early Universe, during radiation dominated phase

influence on

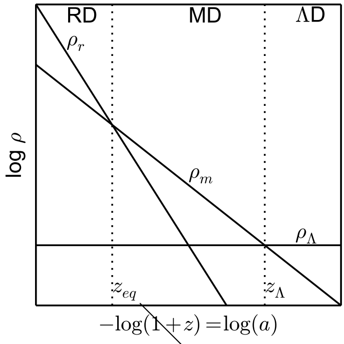
Big Bang Nucleosynthesis: production of light nuclei → abundances today

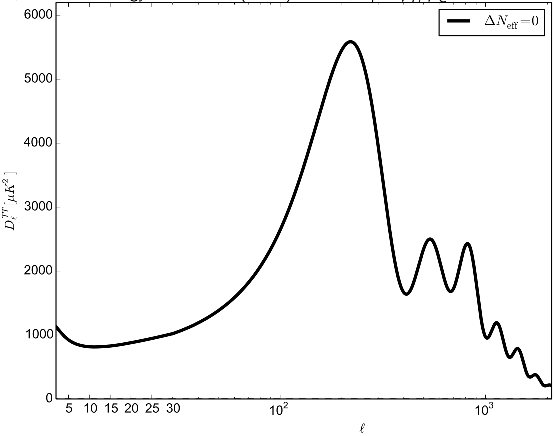
matter-radiation equality → expansion rate at CMB decoupling

Additional Radiation: Effects on the CMB

Starting configuration:

RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z)=a^{-1}$; $\omega_i=\rho_i/\rho_C$



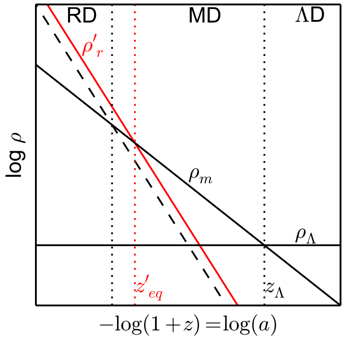


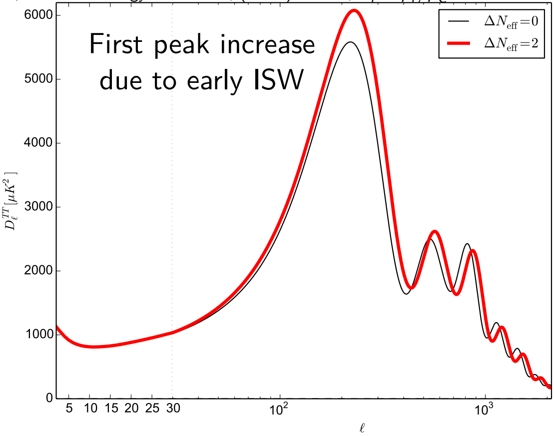
$$1+z_{\rm eq}=\frac{\omega_m}{\omega_r}=\frac{\omega_m}{\omega_\gamma}\frac{1}{1+0.2271\,N_{\rm eff}}$$

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, all the other parameters fixed:

RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z)=a^{-1}$; $\omega_i=\rho_i/\rho_C$





At z_{CMB}: higher $H \propto \rho_r \Rightarrow$ smaller comoving sound horizon $r_s \propto H^{-1}$

$\Rightarrow$ decrease of the angular scale of the acoustic peaks $\theta_s = r_s/D_A$

$\Rightarrow$ shift of the peaks at higher ℓ

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, plus ω_m to fix $z_{\rm eq}$:

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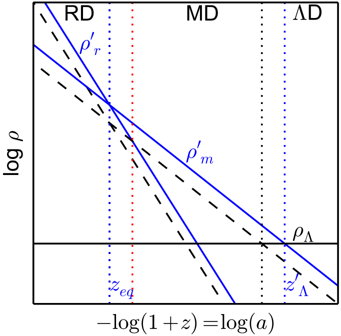
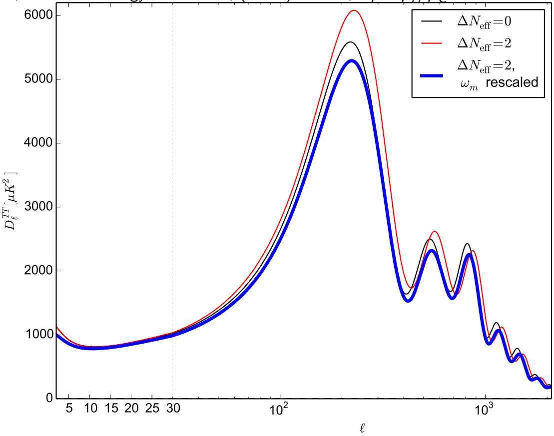


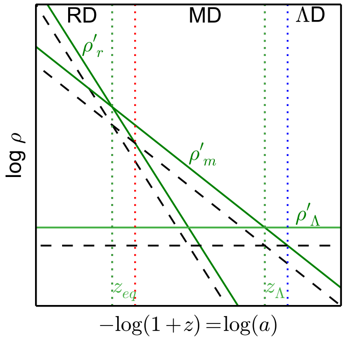


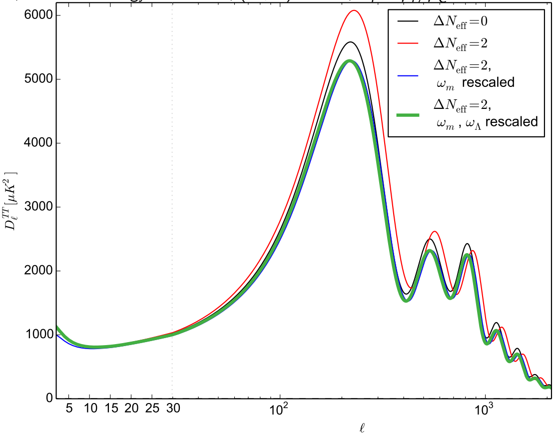
- Contribution from early ISW effect restored (first peak)
- different slope of the Sachs-Wolfe plateau, peak positions, envelope of high-ℓ peaks ⇒ due to later z_Λ

Additional Radiation: Effects on the CMB

If we increase $N_{\rm eff}$, plus ω_m, ω_Λ to fix $z_{\rm eq}$, z_Λ:

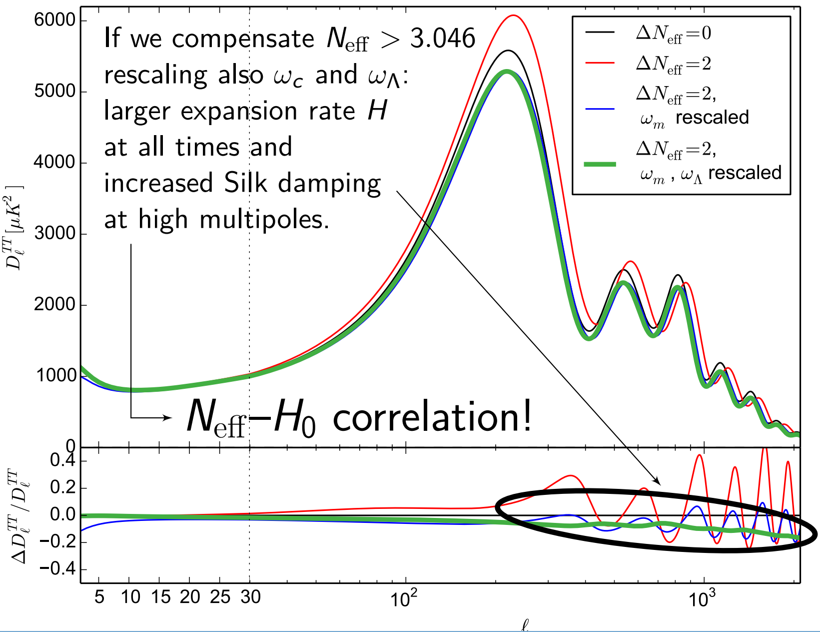
RD: Radiation Dominated, MD: Matter Dominated, ΛD: Dark Energy Dominated; $(1+z) = a^{-1}$; $\omega_i = \rho_i/\rho_C$





- peak positions recovered;
- slope of the Sachs-Wolfe plateau recovered;
- peak amplitude not recovered!

Additional Radiation: Effects on the CMB



$N_{\rm eff}$ and BBN

BBN: production of light nuclei at $t \sim 1$s to $t \sim \mathcal{O}(10^2)$s

temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out:

$$\Gamma_{n\leftrightarrow p} \sim G_F^2 T^5 = H \sim \sqrt{g_\star G_N} T^2$$

↓

$$T_{fr} \simeq (g_\star G_N / G_F^4)^{1/6}$$

enters

$$n/p = \exp(-Q/T_{fr})$$

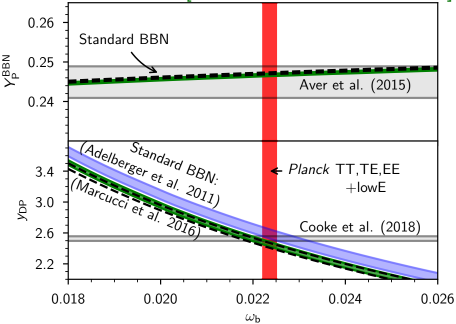
which controls element abundances

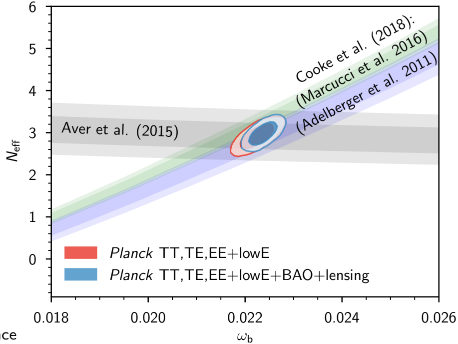
$g_\star$ depends on $N_{\rm eff}$

↓

abundances depend on $N_{\rm eff}$

[Planck Collaboration, 2018]





G_F Fermi constant
G_N Newton constant

n, p: neutron, proton density number
$Q = 1.293$ MeV neutron–proton mass difference

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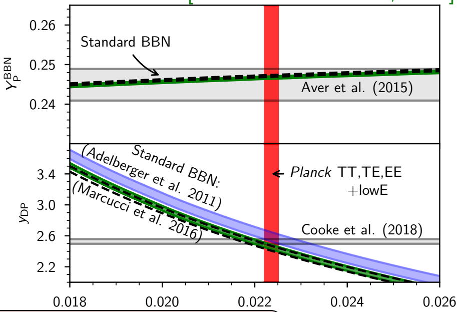
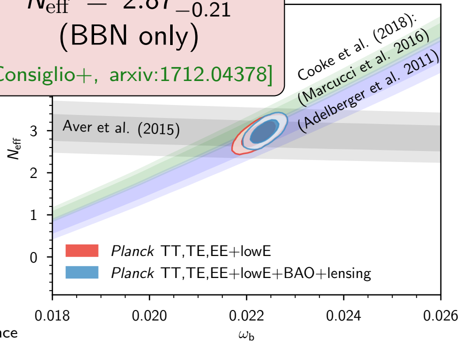


$N_{\text{eff}} = 2.87^{+0.24}_{-0.21}$
(BBN only)
[Consiglio+, arxiv:1712.04378]



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Neutrino masses from CMB

ω_i energy density of species i,
$i \in$ (*r*adiation, *m*atter, *b*aryons, *c*old dark matter, ν)
$z_{\rm eq}$ matter-radiation equality redshift

$$1 + z_{\rm eq} = (\omega_b + \omega_c)/\omega_r$$

independent of m_ν

$$\omega_m^0 = \omega_b^0 + \omega_c^0 + \omega_\nu^0 \text{ today}$$

mass of species relativistic at recombination
affects late time evolution only

small effects on the SW plateau
(cosmic variance, degeneracies...)

Effects on the early ISW effect

$$\frac{\Delta C_\ell}{C_\ell} \simeq -\left(\frac{\sum m_\nu}{0.1\text{ eV}}\right)\%$$

effects on the position of peaks

$$\theta_s = r_s(\eta_{LS})/D_A(\eta_{LS})$$

$$D_A = \int_0^{z_{rec}} \frac{dz}{H(z)}$$

(this effect can be compensated reducing H_0)

correlation m_ν–H_0

["Neutrino Cosmology", Lesgourgues et al.]

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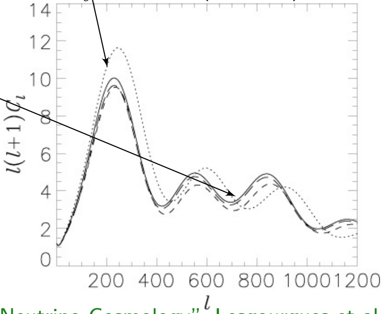


[“Neutrino Cosmology”, Lesgourgues et al.]

Free-streaming - I

Non-cold relics $\Longrightarrow$ damping in the perturbations due to free-streaming

Growth equation: $\ddot{\delta} + \boxed{2H\dot{\delta}} - \boxed{c_s^2 k^2 \frac{\delta}{a^2}} = \boxed{4\pi G_N \rho\, \delta}$

Hubble drag — pressure — gravity

Jeans scale: pressure=gravity

$$k_J \equiv \sqrt{\frac{4\pi G_N \rho}{c_s^2 (1+z)^2}}$$

$k < k_J$: growth of density perturbations

$k > k_J$: no growth can occur

neutrino free-streaming scale

$$k_{fs}(z) \equiv \sqrt{\frac{3}{2}} \frac{H(z)}{(1+z)\sigma_{v,\nu}(z)} \simeq 0.7 \left(\frac{m_\nu}{1\text{ eV}}\right) \sqrt{\frac{\Omega_M}{1+z}}\, h/\text{Mpc}$$

ρ energy density of a given fluid
$\delta = \delta\rho/\rho$ perturbation (single fluid)
c_s sound speed of the fluid
$\sigma_{v,\nu}(z)$ ν velocity dispersion
$H = H(z)$ Hubble factor at redshift z
h reduced Hubble factor today

Free-streaming - II

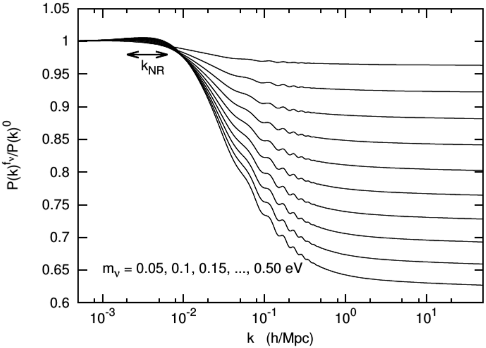
Damping occurs for all $k \gtrsim k_{\rm nr}$

k_{nr}: corresponding
to ν non-relativistic transition

Plot: $\dfrac{P_{m_\nu>0}(k)}{P_{m_\nu=0}(k)}$

- top to bottom: $m_\nu = 0.05$ eV
  to $m_\nu = 0.5$ eV
- $\dfrac{\Delta P}{P} \simeq -\dfrac{8\Omega_\nu}{\Omega_M} \simeq -\dfrac{\sum m_\nu}{0.01\ \mathrm{eV}}\%$

["Neutrino Cosmology", Lesgourgues et al.]
(fixed h, ω_m, ω_b, ω_Λ)

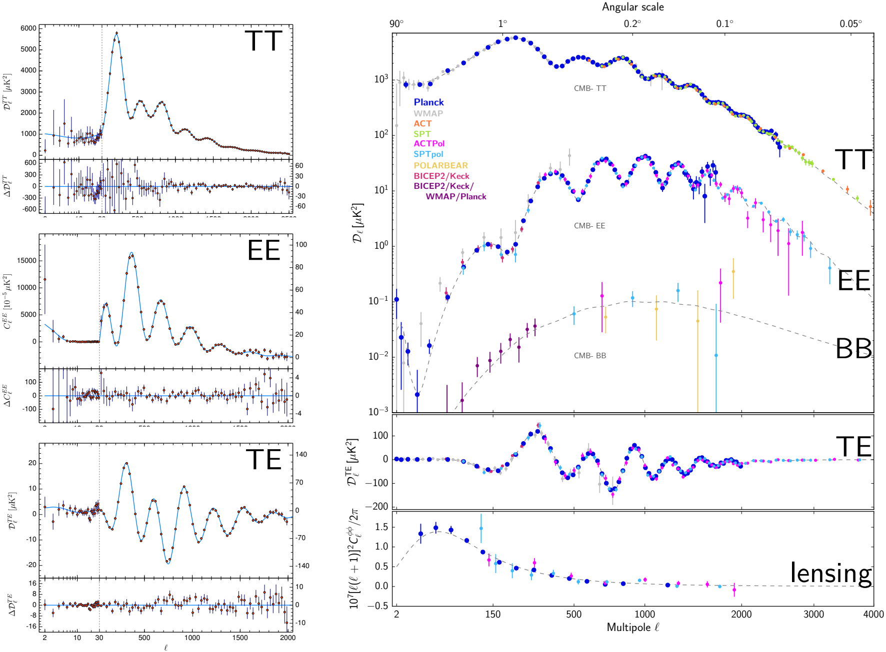


Expected constraints from future surveys:

- Planck CMB + DES: $\sigma(m_\nu) \simeq 0.04$–$0.06$ eV [Font-Ribera et al., 2014]
- Planck CMB + Euclid: $\sigma(m_\nu) \simeq 0.03$ eV [Audren et al., 2013]

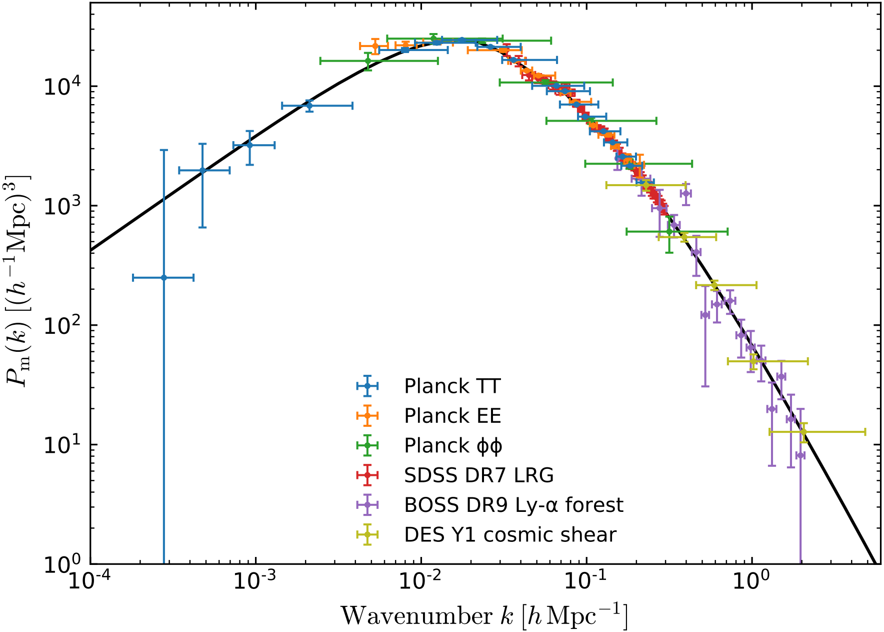
CMB spectra as of 2018

[Planck Collaboration, 2018]



(Linear) matter power spectrum

[Planck Collaboration, 2018]



Tension I: the Hubble parameter H_0

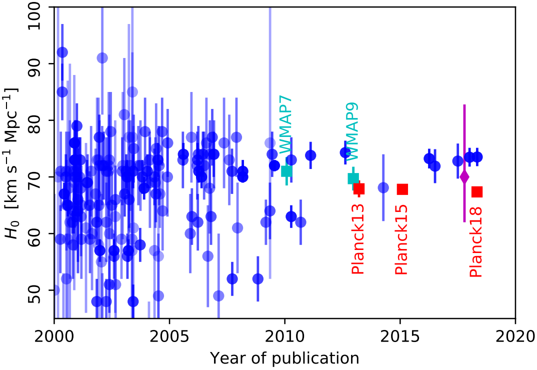
[Planck Collaboration, 2018]

$$v = H_0 d,$$
with $H_0 = H(z = 0)$

Local measurements:
$H(z = 0)$,
local and independent on evolution (model independent, but **systematics?**)

CMB measurements
(probe $z \simeq 1100$):
H_0 from the cosmological evolution (model dependent, well controlled systematics)

68% CL error bars



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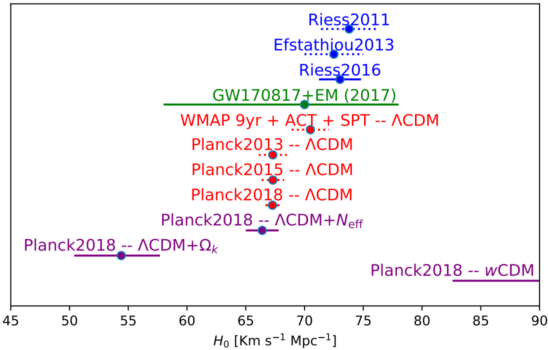

Using HST Cepheids:
[Efstathiou 2013] $H_0 = 72.5 \pm 2.5\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Riess et al., 2016] $H_0 = 73.24 \pm 1.74\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

GW: [Abbott et al., 2017] $H_0 = 70^{+12}_{-8}\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

(ΛCDM model - CMB data only)
[Planck 2013]: $H_0 = 67.3 \pm 1.2\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$
[Planck 2018]: $H_0 = 67.27 \pm 0.60\,\text{Km s}^{-1}\ \text{Mpc}^{-1}$

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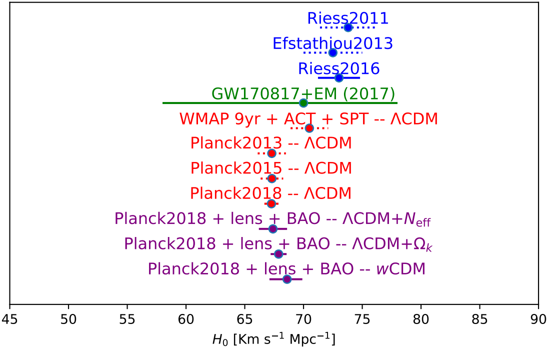

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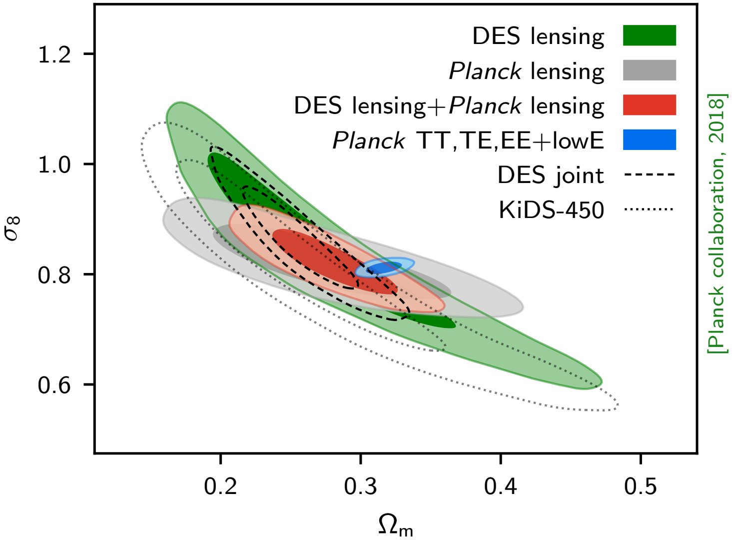
Tension II (?): the matter distribution at small scales

Assuming ΛCDM model:

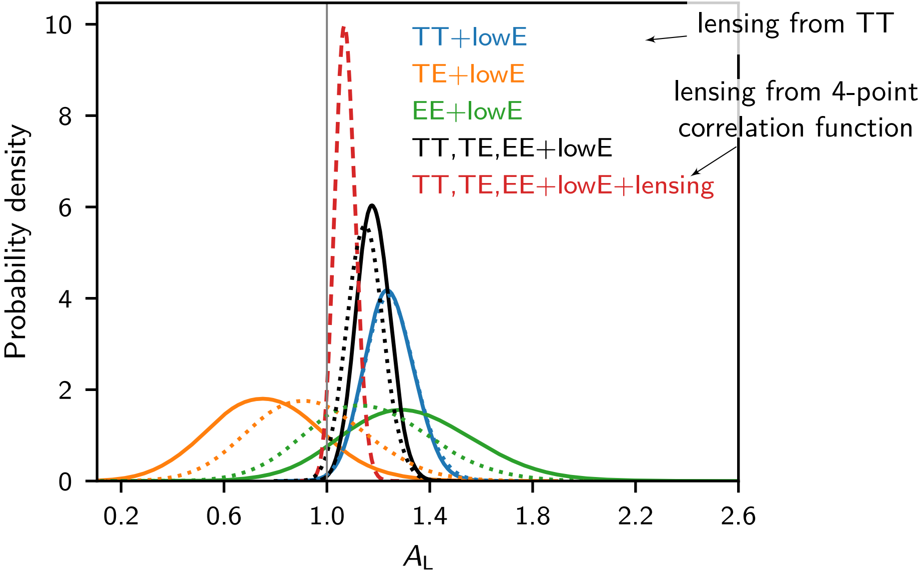
σ_8: rms fluctuation in total matter (baryons + CDM + neutrinos) in $8h^{-1}$ Mpc spheres, today;

Ω_m: total matter density today divided by the critical density



Planck and CMB lensing

[Planck Collaboration, 2018]



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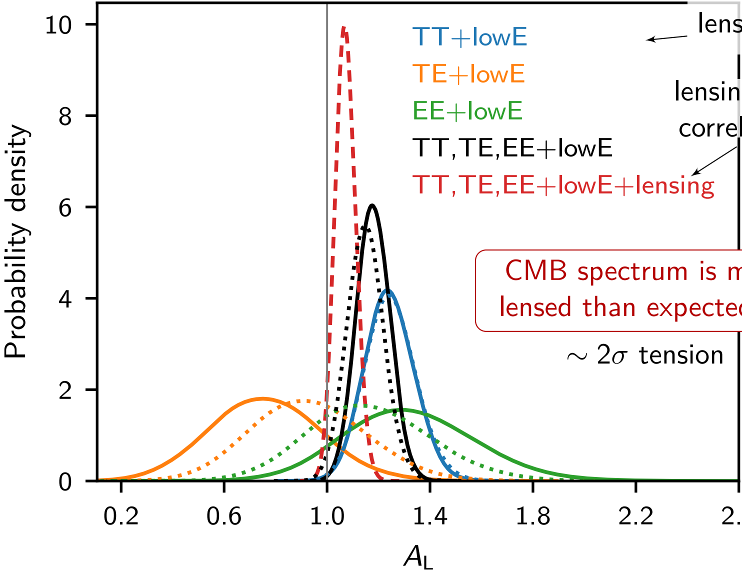


lensing from TT

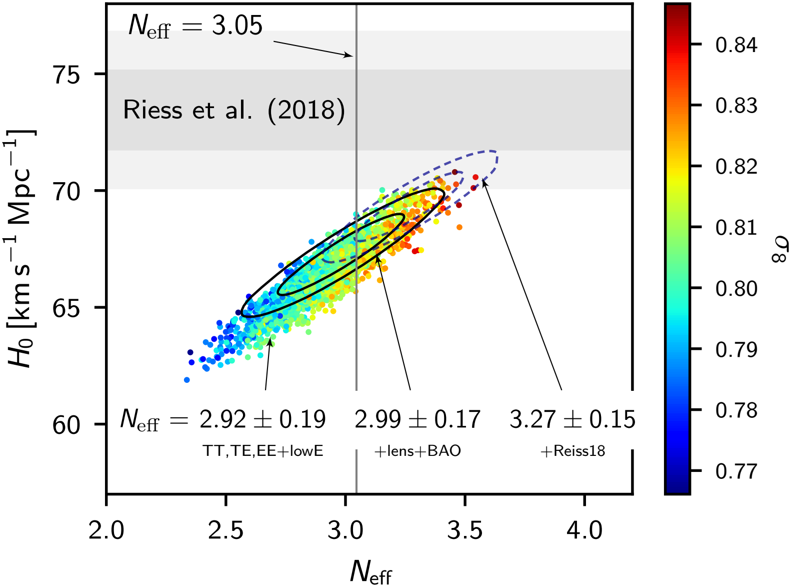
lensing from 4-point correlation function

CMB spectrum is more lensed than expected...

$\sim 2\sigma$ tension

$N_{\rm eff}$ and the local tensions

[Planck Collaboration, 2018]



$N_{\rm eff}$ and the local tensions

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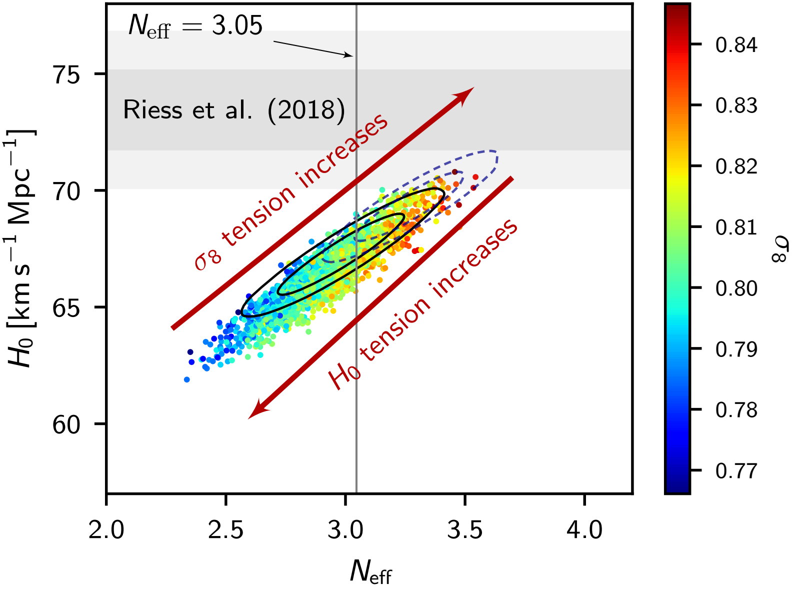
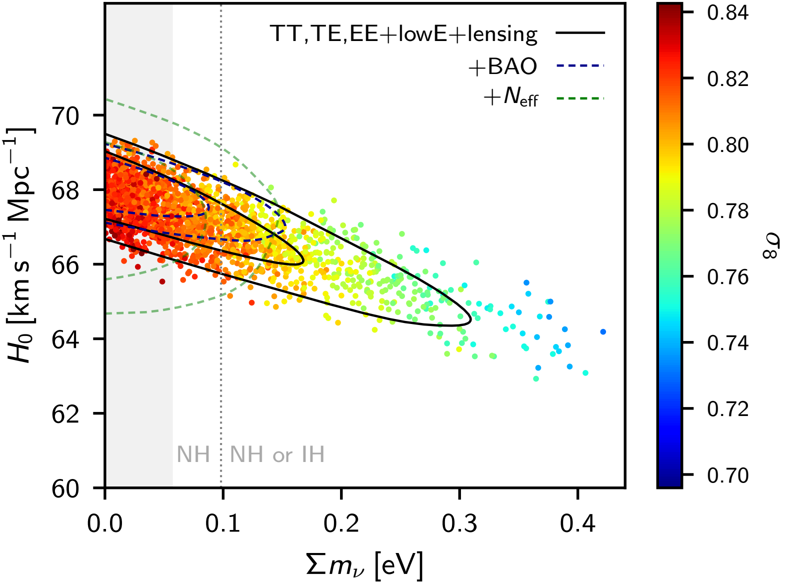


Σm_ν and the local tensions - I

[Planck Collaboration, 2018]



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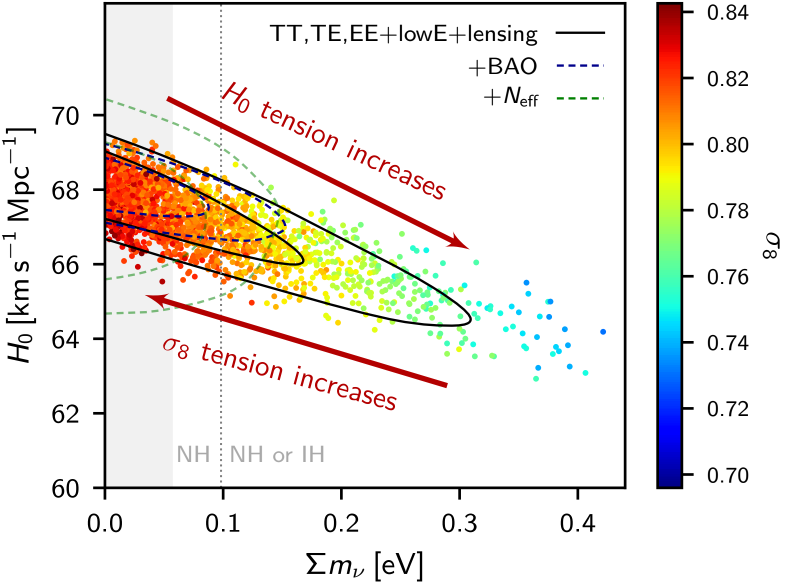
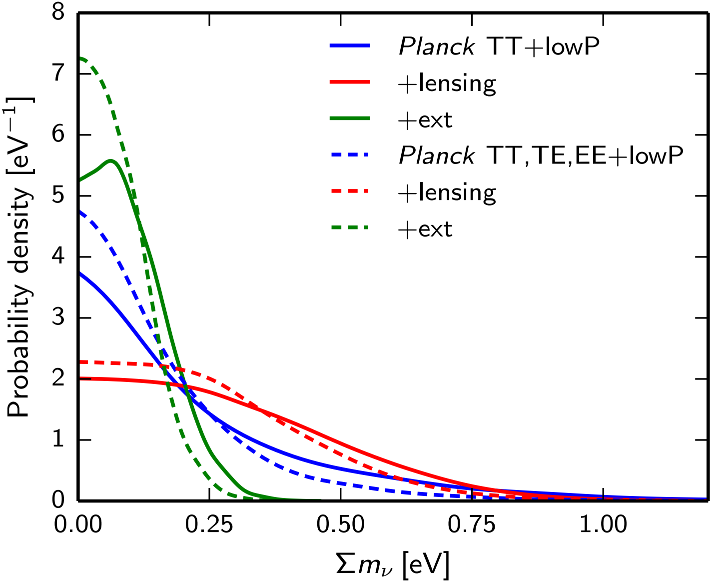


Neutrino masses and CMB lensing

[Planck Collaboration, 2015]



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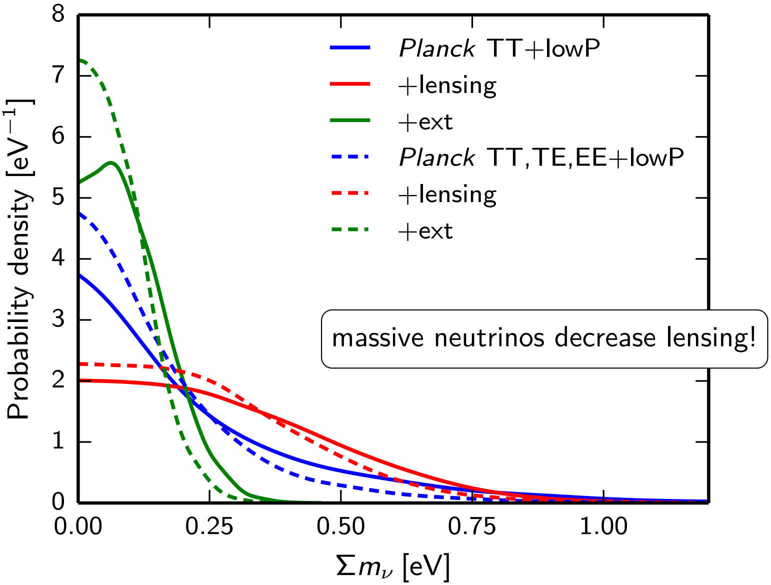


Neutrinos and their masses

[de Salas et al., arxiv:1806.11051]

Normal ordering (NO)

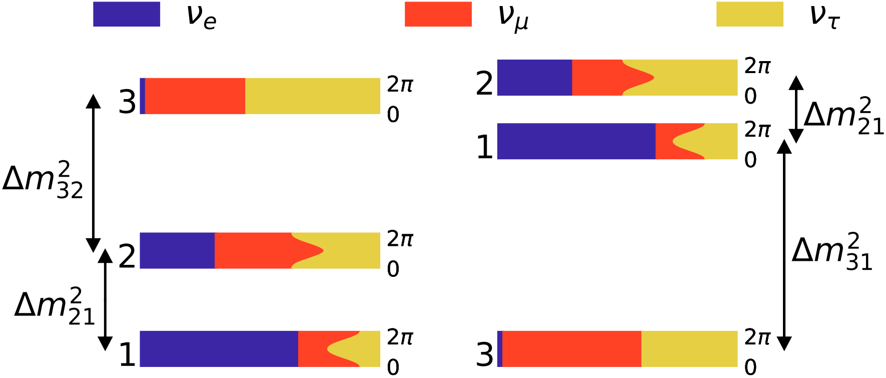
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

$\sum m_k \gtrsim 0.1$ eV



Absolute scale unknown!

Can we constrain the mass ordering using bounds on $\sum m_\nu$?

Playing with priors

Bayes theorem:

$$p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_{\mathcal{M}}}$$

posterior depends on prior!

parameters θ, model $\mathcal{M}$, data d $\pi(\theta|\mathcal{M})$ prior $p(\theta|d,\mathcal{M})$ posterior $\mathcal{L}(\theta)$ likelihood $Z_{\mathcal{M}}$ Bayesian evidence

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$$p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_{\mathcal{M}}}$$

posterior depends on prior!

[Planck 2018]: prior

$0 < \Sigma m_\nu < \mathcal{O}(1)$ eV

strongest upper limit (95%):

$\Sigma m_\nu < 113$ meV

(CMB+lens+BAO+SN)

corresponding to

$\Sigma m_\nu < 53.6$ meV (68%)

below minimum for NO!
does it make sense?

parameters θ, model $\mathcal{M}$, data d $\pi(\theta|\mathcal{M})$ prior $p(\theta|d,\mathcal{M})$ posterior $\mathcal{L}(\theta)$ likelihood $Z_{\mathcal{M}}$ Bayesian evidence

Playing with priors

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$$p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_\mathcal{M}}$$

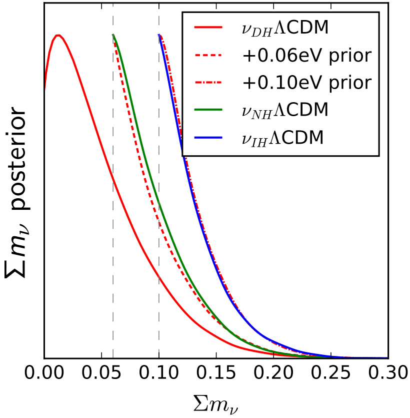
posterior depends on prior!

[Wang+, 2017]

degenerate (DH)
vs normal (NH)
vs inverted (IH) hierarchy

(i.e. change the prior lower bound)

Different limits if you consider simply $\Sigma m_\nu > 0$ or you take into account oscillation results...



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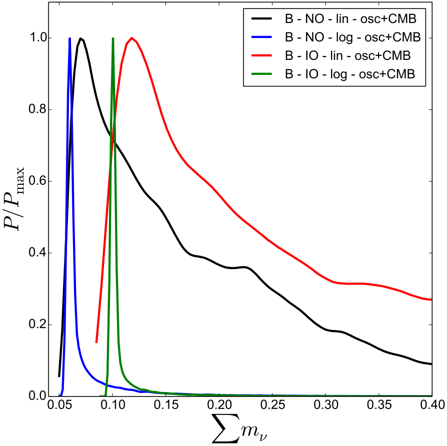
$$p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_{\mathcal{M}}}$$

posterior depends on prior!

[SG+, 2018]

logarithmic
vs linear prior
on $m_{\rm lightest}$

You can artificially tighten the bounds on Σm_ν with different priors. . .



parameters θ, model $\mathcal{M}$, data d $\quad$ $\pi(\theta|\mathcal{M})$ prior $\quad$ $p(\theta|d,\mathcal{M})$ posterior $\quad$ $\mathcal{L}(\theta)$ likelihood $\quad$ $Z_{\mathcal{M}}$ Bayesian evidence

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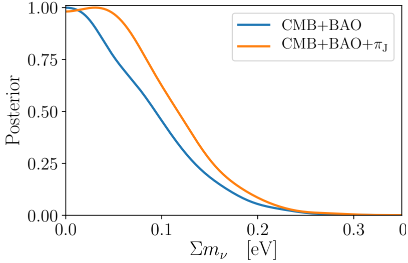
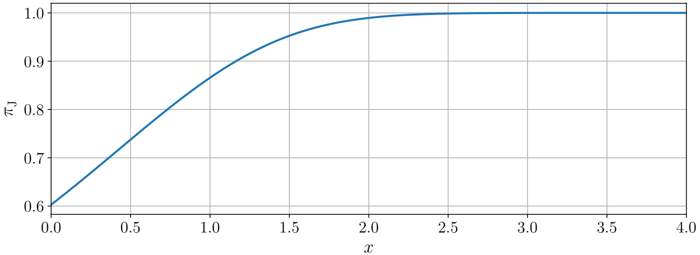


[Hannestad+, 2017]

Jeffreys prior (π_J) for Σm_ν

π_J makes the posterior maximally sensitive to data
for constrained parameter, compensate border effect



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Playing with the baseline model

what if we release the assumption of the ΛCDM model?

CMB TT + lens		CMB TT + lens + BAO
CMB TT,TE,EE		**CMB TT,TE,EE + BAO**
	[Planck 2015]	
$\Sigma m_\nu < 0.68$ eV	ΛCDM	$\Sigma m_\nu < 0.25$ eV
$\Sigma m_\nu < 0.49$ eV		$\Sigma m_\nu < 0.17$ eV

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-	wCDM free dark energy equation of state $w \neq -1$	$\Sigma m_\nu < 0.37$ eV [Planck 2015] $\Sigma m_\nu < 0.27$ eV [Wang+, 2016]

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-	[Planck 2015] ΛCDM+$A_{\rm lens}$ free phenomenological lensing amplitude $A_{\rm lens} \neq -1$	$\Sigma m_\nu < 0.41$ eV

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CMB TT + lens / CMB TT,TE,EE	Model	CMB TT + lens + BAO / CMB TT,TE,EE + BAO
$\Sigma m_\nu < 0.68$ eV $\Sigma m_\nu < 0.49$ eV	[Planck 2015] ΛCDM	$\Sigma m_\nu < 0.25$ eV $\Sigma m_\nu < 0.17$ eV
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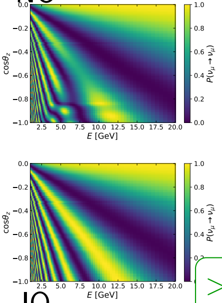
-	[Planck 2015] ΛCDM+$A_{\rm lens}$ free phenomenological lensing amplitude $A_{\rm lens} \neq -1$	$\Sigma m_\nu < 0.41$ eV
$\Sigma m_\nu < 0.96$ eV	[Di Valentino+, 2015] eCDM 12-parameters cosmological model, ΛCDM based	$\Sigma m_\nu < 0.53$ eV

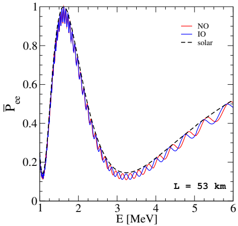
Constraining the mass ordering

[de Salas et al., arxiv:1806.11051]

NO

oscillations





IO

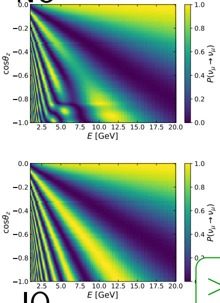
$> 3\sigma$ preference for NO

Constraining the mass ordering

[de Salas et al., arxiv:1806.11051]

oscillations

NO



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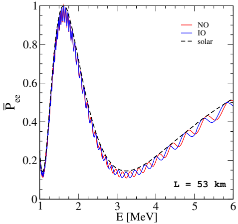

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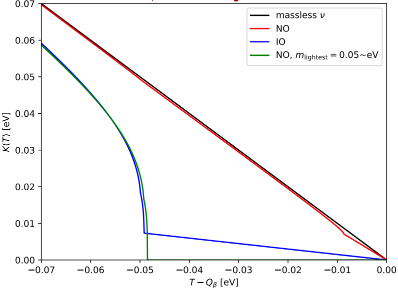
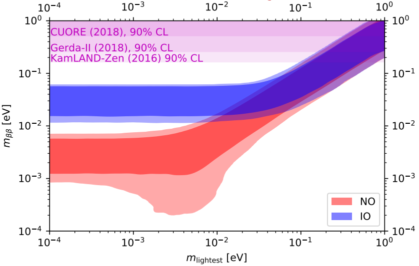
β decay



$0\nu\beta\beta$ decay



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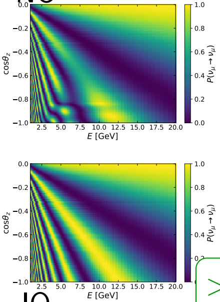

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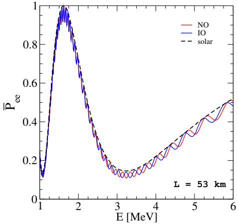

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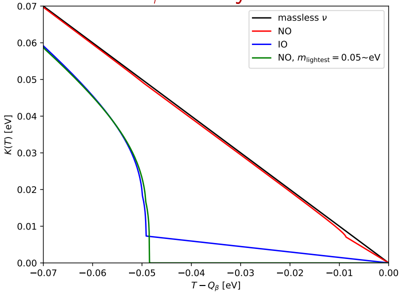

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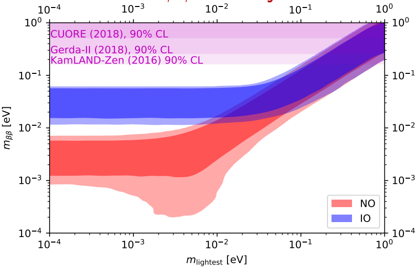
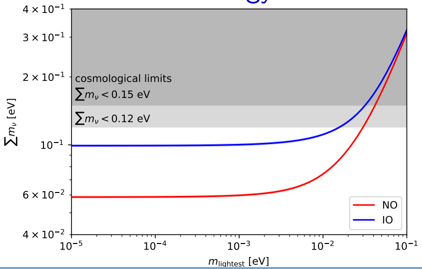


cosmology



(Bayesian) results

[de Salas et al., arxiv:1806.11051]

Bayes theorem for models:

$$p(\mathcal{M}|d) \propto Z_{\mathcal{M}}\pi(\mathcal{M})$$

Bayesian evidence:

$$Z_{\mathcal{M}} = \int_{\Omega_{\mathcal{M}}} \mathcal{L}(\theta)\,\pi(\theta)\,d\theta$$

Bayes factor NO vs IO:

$$B_{\rm NO,IO} = Z_{\rm NO}/Z_{\rm IO}$$

Posterior probability:

$$\begin{aligned} P_{\rm NO} &= B_{\rm NO,IO}/(B_{\rm NO,IO}+1) \\ P_{\rm IO} &= 1/(B_{\rm NO,IO}+1) \end{aligned}$$

$\pi(\mathcal{M})$ model prior
$p(\mathcal{M}|d)$ model posterior
$\mathcal{L}(\theta)$ likelihood
$\Omega_{\mathcal{M}}$ parameter space, for parameters θ

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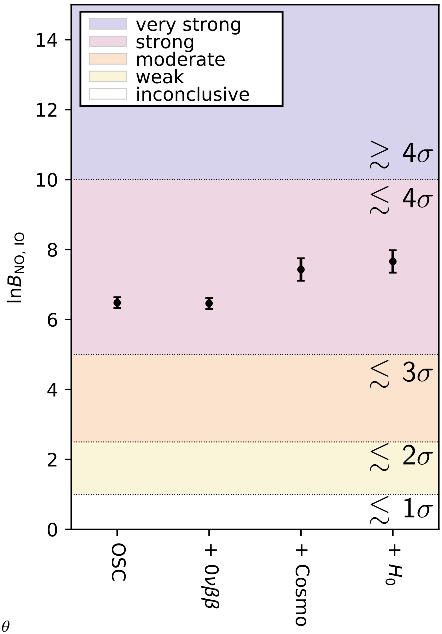


$\pi(\mathcal{M})$ model prior $\quad$ $\mathcal{L}(\theta)$ likelihood

$p(\mathcal{M}|d)$ model posterior $\quad$ $\Omega_{\mathcal{M}}$ parameter space, for parameters θ

A viable detection method

[Long et al., JCAP 08 (2014) 038]

How to directly detect non-relativistic neutrinos?

Remember that $\langle E_\nu \rangle \simeq \mathcal{O}(10^{-4})$ eV today $\longrightarrow$ a process without energy threshold is necessary

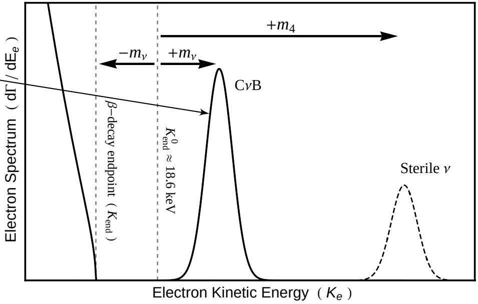
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

Main background: β decay $n \to p + e^- + \bar{\nu}$!

signal is a peak at $2m_\nu$ above β–decay endpoint

only with a lot of material

need a very good energy resolution



PTOLEMY

[Long et al., JCAP 08 (2014) 038]
[Betts et al., arxiv:1307.4738]
[PTOLEMY LoI, arxiv:1808.01892]

PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution $\Delta \simeq 0.1$ eV? 0.05 eV? ⟷ built mainly for CNB

→ can probe $m_\nu \simeq 1.4\Delta \simeq 0.1$ eV

→ $M_T = 100$ g of atomic ^{3}H

$$\Gamma_{\text{CNB}} = \sum_{i=1}^{3} |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})]\, N_T\, \bar{\sigma} \quad \sim \mathcal{O}(10)\ \text{yr}^{-1}$$

N_T number of ^{3}H nuclei in a sample of mass M_T $\bar{\sigma} \simeq 3.834 \times 10^{-45}$ cm^2 n_i number density of neutrino i

(without clustering)

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ehnancement from ν clustering in the galaxy?

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(without clustering)

Detection of the relic neutrinos

[PTOLEMY LoI, arxiv:1808.01892]

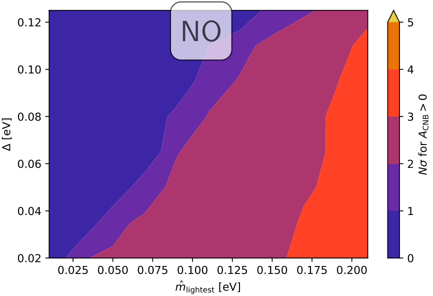
using the definition:

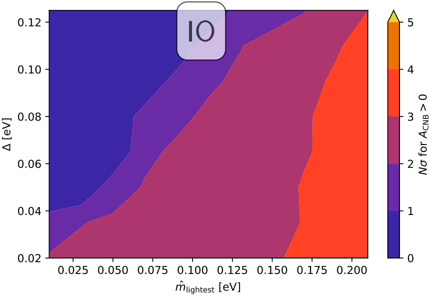
$$N^i_{\rm th}(\boldsymbol{\theta}) = A_\beta N^i_\beta(\hat{E}_{end} + \Delta E_{end}, m_i, U) + \boldsymbol{A}_{\rm CNB} N^i_{\rm CNB}(\hat{E}_{end} + \Delta E_{end}, m_i, U) + N_b$$

if $\boldsymbol{A}_{\rm CNB} > 0$ at $N\sigma$, direct detection of CNB accomplished at $N\sigma$

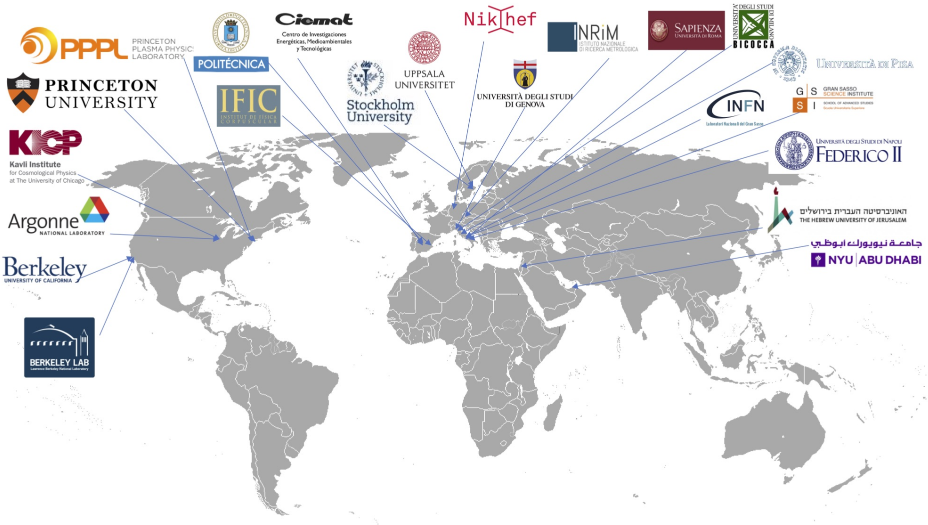
statistical only!

significance on $A_{\rm CNB} > 0$
as a function of $\hat{m}_{\rm lightest}$, Δ





PTOLEMY collaboration



Conclusions

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Cosmology is an excellent tool
for studying neutrino properties!

In particular, **masses** and **effective number**

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But beware of systematics/model dependency!
Situation less clear than what usually stated?

In particular: **priors**, **model extensions**

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We need more data in order to
break degeneracies
between different parameters!

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Bonus

For a not-so-near future:
direct detection of relic neutrinos**???**
A long way to go. . .

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Bonus

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Thank you for the attention!

β and Neutrino Capture spectra

[PTOLEMY LoI, arxiv:1808.01892]

$$\frac{d\widetilde{\Gamma}_{\rm CNB}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{i=1}^{N_\nu}\bar\sigma\, N_T\,|U_{ei}|^2\, f_{c,i}\, n_0 \times e^{-\frac{[E_e-(E_{\rm end}+m_i+m_{\rm lightest})]^2}{2\sigma^2}}$$

$$\frac{d\Gamma_\beta}{dE_e} = \frac{\bar\sigma}{\pi^2} N_T \sum_{i=1}^{N_\nu}|U_{ei}|^2 H(E_e, m_i)$$

$$\frac{d\widetilde{\Gamma}_\beta}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty} dx\, \frac{d\Gamma_\beta}{dE_e}(x)\, \exp\left[-\frac{(E_e-x)^2}{2\sigma^2}\right]$$

$\bar\sigma$ cross section, N_T number of tritium atoms in $M_T = 100$ g, $E_{\rm end}$ endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation

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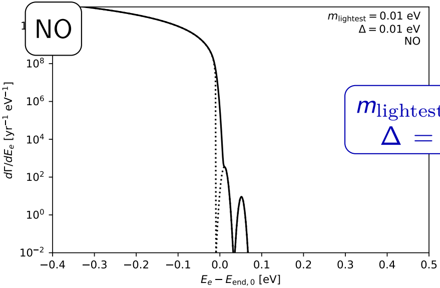
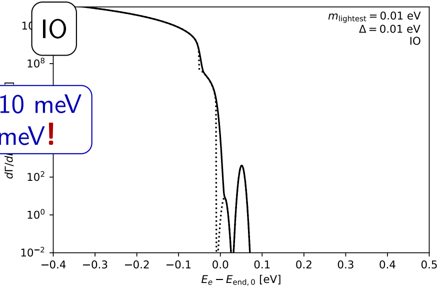


$m_{\rm lightest} = 10$ meV
$\Delta = 10$ meV!



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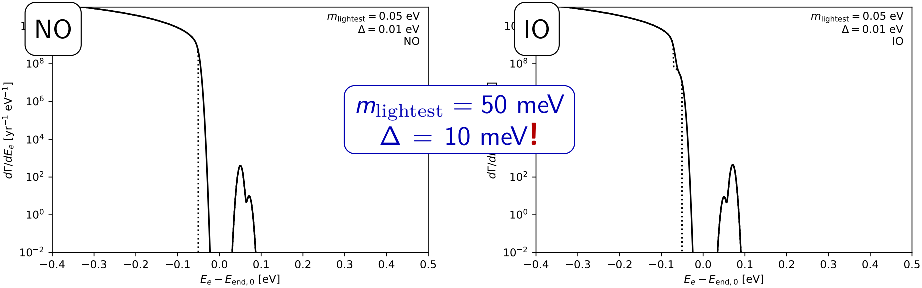

$m_{\rm lightest} = 50$ meV
$\Delta = 10$ meV**!**

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$$\frac{d\widetilde{\Gamma}_{\rm CNB}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{i=1}^{N_\nu}\bar{\sigma}\, N_T\, |U_{ei}|^2\, f_{c,i}\, n_0 \times e^{-\frac{[E_e-(E_{\rm end}+m_i+m_{\rm lightest})]^2}{2\sigma^2}}$$

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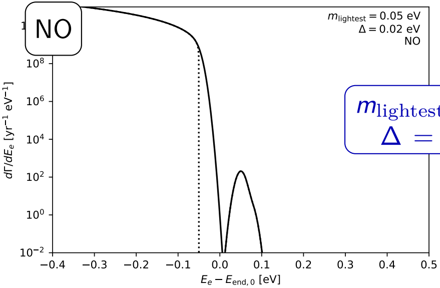
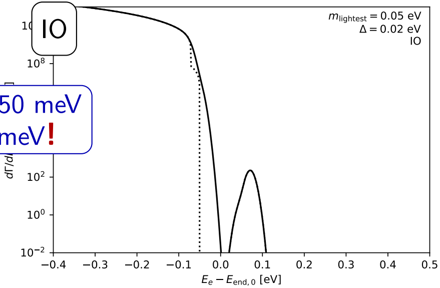
$$\frac{d\widetilde{\Gamma}_\beta}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty} dx\, \frac{d\Gamma_\beta}{dE_e}(x)\, \exp\left[-\frac{(E_e-x)^2}{2\sigma^2}\right]$$



$m_{\rm lightest} = 50$ meV
$\Delta = 20$ meV**!**



$\bar{\sigma}$ cross section, N_T number of tritium atoms in $M_T = 100$ g, $E_{\rm end}$ endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation

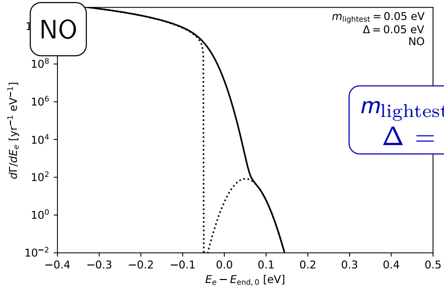
β and Neutrino Capture spectra

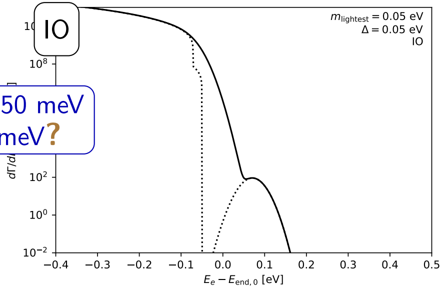
[PTOLEMY LoI, arxiv:1808.01892]

$$\frac{d\widetilde{\Gamma}_{\rm CNB}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{i=1}^{N_\nu} \bar{\sigma}\, N_T\, |U_{ei}|^2\, f_{c,i}\, n_0 \times e^{-\frac{[E_e-(E_{\rm end}+m_i+m_{\rm lightest})]^2}{2\sigma^2}}$$

$$\frac{d\Gamma_\beta}{dE_e} = \frac{\bar{\sigma}}{\pi^2} N_T \sum_{i=1}^{N_\nu} |U_{ei}|^2 H(E_e, m_i)$$

$$\frac{d\widetilde{\Gamma}_\beta}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty} dx\, \frac{d\Gamma_\beta}{dE_e}(x)\, \exp\left[-\frac{(E_e-x)^2}{2\sigma^2}\right]$$





$m_{\rm lightest} = 50$ meV
$\Delta = 50$ meV?

$\bar{\sigma}$ cross section, N_T number of tritium atoms in $M_T = 100$ g, $E_{\rm end}$ endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation